

**SCHOOL OF  
CIVIL ENGINEERING  
INDIANA  
DEPARTMENT OF TRANSPORTATION**

## JOINT HIGHWAY RESEARCH PROJECT

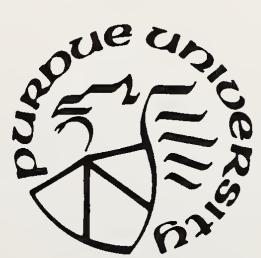
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## Final Report, Vol. 1

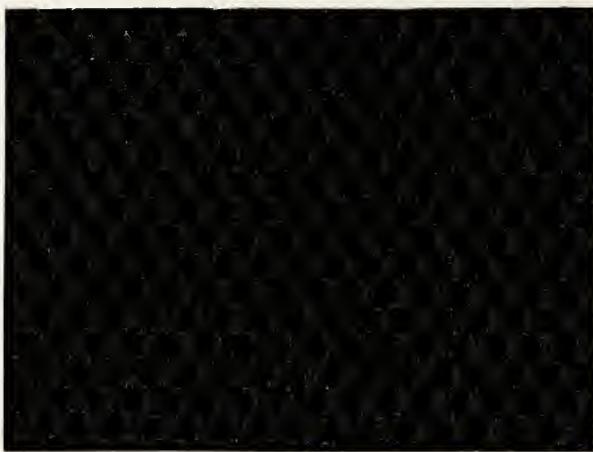
THE DEVELOPMENT OF OPTIMAL  
STRATEGIES FOR MAINTENANCE,  
REHABILITATION AND REPLACEMENT  
OF HIGHWAY BRIDGES, FINAL  
REPORT VOL 1: THE ELEMENTS OF  
INDIANA BRIDGE MANAGEMENT  
SYSTEM (IBMS)

Kumares C. Sinha  
Mitsuru Saito  
Yi Jiang

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Ah-Beng Tee  
Mark D. Bowman



PURDUE UNIVERSITY



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## FINAL REPORT

The Development of Optimal Strategies for Maintenance Rehabilitation  
and Replacement of Highway Bridges,  
Final Report Vol. 1: The Elements Of The Indiana Bridge Management System

TO: Harold L. Michael, Director August 15, 1989  
Joint Highway Research Project Revised August 15, 1989  
Revised January 22, 1991  
FROM: Kumares C. Sinha, Research Engineer Project: C-36-731  
Joint Highway Research Project File: 3-4-10

Attached is the Vol. 1 of the Final Report on the HPR Part II Study entitled, "The Development of Optimal Strategies for Maintenance Rehabilitation and Replacement of Highway Bridges." This volume provides an overview of the various components of the Indiana Bridge Management System developed in the study. It covers all ten tasks of the study and highlights the organization and data management aspects of the system. The research reported in this volume was conducted under my directions.

This report is forwarded for review, comment and acceptance by the INDOT and FHWA as partial fulfillment of the objectives of the research.

Respectfully submitted,

*Kelisa*  
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THE DEVELOPMENT OF OPTIMAL STRATEGIES FOR MAINTENANCE,  
REHABILITATION AND REPLACEMENT OF HIGHWAY BRIDGES  
FINAL REPORT VOL. 1: THE ELEMENTS OF THE INDIANA BRIDGE MANAGEMENT SYSTEM

Final Report

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and the

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Federal Highway Administration

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessary reflect the official views or policies of The Federal Highway Administration. This report does not constitute a standard, specification, or a regulation.

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The titles of all six volumes are listed below.			
<ol style="list-style-type: none"> <li>1. The Elements of Indiana Bridge Management (IBMS)</li> <li>2. A System for Bridge Structural Condition Assessment</li> <li>3. Bridge Traffic Safety Evaluation</li> <li>4. Cost Analysis</li> <li>5. Priority Ranking Method</li> <li>6. Performance Analysis and Optimization</li> </ol>			
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## CHAPTER ONE

### INTRODUCTION

#### 1.1 Background Information

In recent years there has been a growing concern about the safety of existing bridges. The major elements of the bridge problem are aging and obsolescence. About one-half of the approximately 600,000 highway bridges in the U.S. were built before 1940 [Reilly 1983]. In 1985, seventy-five percent of all bridges were reported to be older than the typical 50-year design life for bridges [ITE 1985]. Most of these bridges were designed for less traffic, smaller vehicles, slower speed, and lighter loads than the standards employed for recently built bridges. The Federal Highway Administration (FHWA) rated about 45 percent of the existing bridges (248,527) as either functionally or structurally deficient [FHWA 1982].

FHWA classifies the nation's bridges based on the structural as well as functional deficiencies. A bridge is considered structurally deficient if either its deck, superstructure, or substructure has weakened or deteriorated to the point that the bridge is inadequate to support all types of traffic. Structurally deficient bridges must be closed unless proper posting of loading limit is implemented. A functionally obsolete bridge is a bridge that is structurally sound but is no longer adequate to serve present traffic, because of insufficient width, poor alignment with the approach roadway, insufficient underclearance, or insufficient carrying capacity [Tedesco 1983].

Like many other states, Indiana also has a large number of bridges that need immediate attention. There were 5,290 bridges on the state highway sys-

tem in Indiana as of March, 1988, of which 1,798 bridges - or 34% - were functionally obsolete and 472 bridges - or 9% - were rated as structurally deficient. These statistics clearly indicate bridge safety problems that the State of Indiana would face in the near future.

Because of the imbalance between the bridge repair and replacement needs and the fiscal constraint, the development of bridge management systems has recently been stressed. The need for bridge management systems has been greatly influenced by successful research and implementation efforts in pavement management systems and maintenance management systems. Much work, however, is still underway in pavement and routine maintenance management areas.

Little research work has been focused on systematic methodologies that can provide optimal strategies for a comprehensive bridge management system at the network level. Some states have undertaken studies related to the management of bridge repair and replacement [Cady 1981], but little effort has yet been made to examine the bridge management issue on a comprehensive basis. Making decisions on bridge rehabilitation and replacement is still primarily based on subjective and imprecise condition and sufficiency ratings.

The present research was undertaken to develop a method to assess present and future maintenance, rehabilitation, and replacement needs of existing bridges and to develop optimal strategies for an effective management of bridge activities. The scope of the study was defined through discussions with bridge inspectors of the central office as well as the district offices of the Indiana Department of Transportation. In broad terms, the study was divided into four sub-areas: consistency of condition ratings, analysis of bridge improvement costs and impacts, development of performance and needs

assessment models, and development of project selection models. Data bases for this study were compiled from the existing bridge records obtained either from the Indiana Department of Transportation (INDOT) or the Federal Highway Administration's Washington office, and a series of interviews and questionnaire surveys of the bridge inspectors of the district offices and the central office of INDOT.

#### 1.2 Purpose and Scope of Research

The overall research purpose consisted of the following major objectives:

1. Development of a method to better use the existing bridge inspection data in selecting bridges for maintenance, rehabilitation, and replacement;
2. Development of a method to provide consistent and statewide uniform measurements for rating bridges;
3. Analysis of bridge maintenance, rehabilitation, and replacement costs, and analysis of relationships between bridge attributes and costs;
4. Development of a method to estimate remaining service life of bridges and effects of bridge activities on condition rating and service life;
5. Development of a bridge traffic safety evaluation scheme that relates physical characteristics of bridge structure to accident potential;
6. Development of a project selection procedure using life cycle cost analysis, ranking, and optimization method; and
7. Development of a set of guidelines that can be used by the Indiana Department of Transportation in implementing a bridge management system

including data bases, and organizational requirements.

This report discusses the basic elements of the proposed bridge management system for Indiana (IBMS), the procedure for its implementation, and the organizational framework for the IBMS.

### 1.3 Report Organization

This volume of the final report contains four chapters. Chapter 2 presents a detailed overview of the bridge management system developed. Chapter 3 presents the implementation procedure, and the organizational requirements are discussed in Chapter 4.

## CHAPTER TWO

### BRIDGE MANAGEMENT SYSTEM FOR INDOT

#### 2.1 System Modules

The main thrust of the study was to develop a systematic procedure that can help the Program Development Division to program bridge replacement and rehabilitation projects and to assist the Maintenance Division to prepare an appropriate bridge maintenance program. During the study, it was recognized that the need for consistency of input data into a bridge management system was as important as the operation of the system. Therefore, a particular attention was given to the development of procedures that can be used by bridge inspectors to make consistent decisions in the identification of bridge deficiencies. The proposed bridge management system for Indiana (IBMS) would consist of eight (8) essential modules, as listed below.

1. Data Base Module
2. Condition Rating Assistance Module
3. Bridge Safety Evaluation Module
4. Improvement Activity Identification Module
5. Impact Identification Module
6. Project Selection Module
  - a. Life Cycle Costing Sub-Module
  - b. Ranking Sub-Module
  - c. Optimization Sub-Module
7. Activity Recording and Monitoring Module
8. Reporting Module

Figure 2.1 illustrates the interaction of these eight modules within the IBMS. The basic structure proposed here is a modified version of what Hudson et al. recommended in a NCHRP report [Hudson et al. 1987]. The modules and sub-modules are described in the following sections.

## 2.2 Data Base Module

The data base of a bridge management system must contain all necessary information about each state-owned bridge in the system for performing the tasks of the other modules and for preparing various network summary reports. The existing structure inventory and appraisal (SIA) data file contains the inspection data for all bridges and culverts in the state which are longer than 20 feet long. A separate data base that would include the inspection data and other information for the state-owned bridges necessary to implement the proposed IBMS modules needs to be established for the following two reasons. First, reading through the SIA record file every time for running the project selection sub-modules is simply not economical because the state-owned bridges account for only about 5290 records out of the total 17,658 records (as of March, 1988). Second, expanding the existing SIA data file to include the additional variables proposed in the present study may not be an effective use of computer memory storage because approximately three-fourths of the expanded memory storage may not be used for non-state-owned bridges.

Table 2.1 presents a list of variables suggested to be included in the IBMS data base, some of which can be transferred from the existing SIA data base. Definitions of some of the data items are included in other volumes. For example, the details of ranking scores are given in Volume 5. The IBMS data base should be updated whenever some changes take place in the charac-

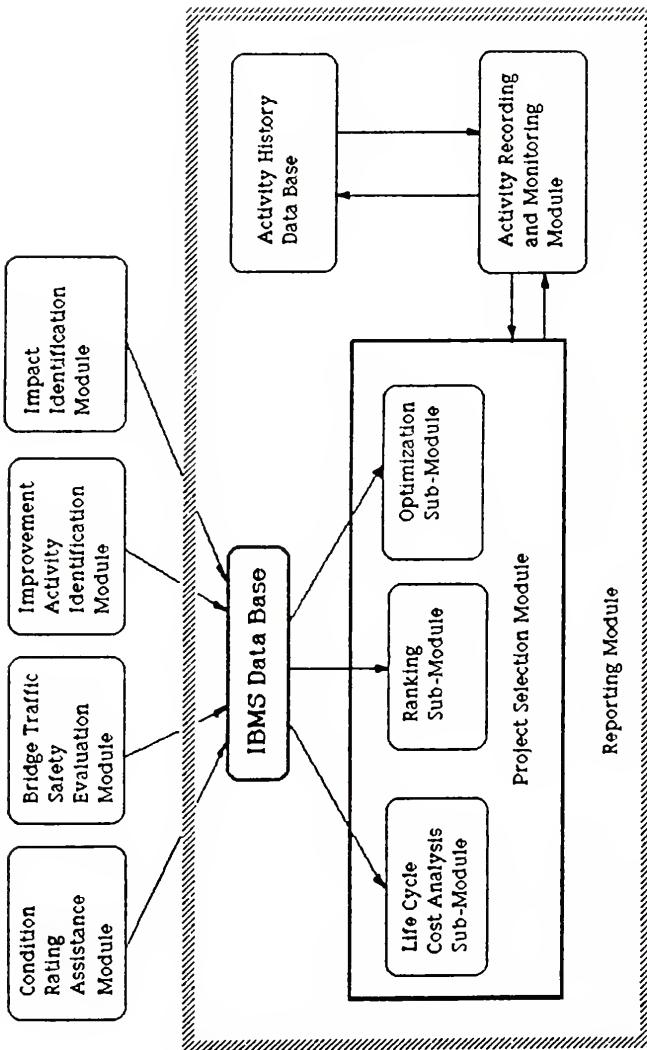


Figure 2.1 Graphical Representation of the Indiana Bridge Management System

Table 2.1 Suggested Contents of IBMS Data Base

A. Bridge Identification Items

1. Structure number
2. Highway classification
3. Route number
4. County number
5. District number
6. Mileage post
7. Bridge reference number

B. Bridge Attribute Data

8. Bridge type
9. Year of new construction
10. Year of last rehabilitation
11. Last contract number
12. Last type of construction (i.e., new construction, replacement, reconstruction, etc.)
13. Feature type crossed (i.e., water, road, RR, combination)
14. Number of spans
15. Span lengths
16. Deck width (out-to-out), if width changes, use average value (weighted by deck lengths)
17. Clear deck width, if width changes, use average value (weighted by deck lengths)
18. Total deck length
19. Vertical clearance
20. Type of deck joints
21. Type of deck protection
22. Bridge skew
23. Number of lanes
24. Average daily traffic (ADT)
25. Percent of trucks
26. Substructure type
27. Approach length
28. Amount of approach earthwork (cubic yards)
29. Loading design (i.e., HS20, Toll Road, special loading and/or earthquake)
30. Railroad or pedestrian bridge
31. Alignment - original, relocated or new bridge
32. Urban or rural location
33. How was traffic maintained last contract
34. Detour length in case of posting or closure
35. Original bridge length and width
36. Letting date
37. Superstructure cost
38. Substructure cost
39. Approach cost
40. Cost of traffic maintenance

Table 2.1 Continued

- 41. Other cost
- 42. Total cost
- C. Bridge Condition Information
  - 43. Deck condition rating
  - 44. Superstructure condition rating
  - 45. Substructure condition rating
  - 46. Approach roadway alignment
  - 47. Waterway adequacy
- D. Bridge Appraisal Related Information
  - 48. Load capacity
  - 49. Deck remaining service life if nothing is done (estimated by inspectors)
  - 50. Superstructure remaining service life if nothing is done (estimated by inspectors)
  - 51. Substructure remaining service life if nothing is done (estimated by inspectors)
  - 52. Bridge traffic safety index (computed)
- E. Proposed Bridge Activity Data (least cost option)
  - 53. Type of activity (P-replacement, H-rehabilitation, M-routine maintenance)
  - 54. Estimates of next capital investment
  - 55. Proposed year of implementation
  - 56. Equivalent uniform annual cost
- F. Ranking Scores (Range from 0.0 to 100.0, with 100.0 being the worst)
  - 57. Total combined score
  - 58. Effectiveness of investment objective score
  - 59. Preservation of investment objective score
  - 60. Bridge traffic safety objective score
  - 61. Community impact score

teristics of bridges.

### 2.3 Condition Rating Assistance Module

The bridge condition rating is a key parameter in determining types of repairs necessary for a bridge. This, together with other inspection data, constitutes basic input data needed for the ranking and optimization procedures. Hence, it is important that the condition rating be carried out in a consistent manner for all bridges. In reality, however, the perfect consistency is difficult to achieve because the task of bridge inspection is highly subjective and does not lend itself to precise estimates. Furthermore, current bridge inspection practices suffer from two inherent shortcomings: (1) difficulties in systematically incorporating subjective judgment into the inspection process; and (2) a lack of established bridge inspection guidelines. Consequently, it is possible that two competent bridge inspectors may assess the condition of a given bridge differently depending on factors such as their job experience.

In spite of these shortcomings, it is generally recognized that the current inspection procedure is functionally adequate for its intended purpose of preventing structural failures of bridges and possibly for scheduling minor repairs. However, for comprehensive bridge management purposes, enhancement to the existing field inspection data is necessary to ensure optimal solution. Consequently, the purpose of this module is to filter the field inspection data of any inconsistencies before entering the bridge mangement system.

In this module, a bridge is divided into three major components: deck, superstructure, and substructure. Each component is further divided into simpler subcomponents. This approach of reducing a complex structure into

simpler elements is called the problem reduction approach in knowledge engineering. The essence of this approach is that it simplifies the original problem. Viewed from the bridge inspection perspective, this approach will promote consistency in the condition assessment process and will effectively reduce the likelihood of omitting significant subcomponents or committing significant assessment errors. The subdivision of a bridge into simpler subcomponents in this module is accomplished by adopting the bridge items listed in a standard field inspection form. The advantage of adopting the items listed in the inspection form is that all existing data bases can be used without modification.

Based on the information gathered from interviews with bridge inspectors and subsequent analysis of inspection data, it was found that the subjective judgment utilized in bridge inspection involves the assessment of the importance of various subcomponents. Each importance factor is a function of both the structural importance of the subcomponent and the severity of deterioration of the subcomponent. If there is no distress in a subcomponent, then the importance factor is essentially equal to the structural importance of the subcomponent. In addition, as the degree of deterioration increases, the importance factor also increases.

Determining the various importance factors is a difficult task. This is partly because there are many bridge subcomponents and many possible states of deterioration. This difficulty is further compounded by the fact that there are many non-structural subcomponents. Thus, the importance factors in this module were obtained primarily via opinion surveys of bridge inspectors and engineers. Some of these importance factors can be further corroborated and refined using structural analyses. Since there are presently no established

guidelines available for the bridge inspector to follow when assessing the importance of the various subcomponents, their responses to the questionnaire would invariably contain uncertainties. To account for these uncertainties, a mathematical theory, called the fuzzy sets theory [Zimmerman 1988], was employed. Using this theory, each importance factor is expressed as a membership function which is an interval estimate with a possibility distribution. To combine the various subcomponent condition ratings and their associated importance factors, a mathematical function, called the cumulative rating function, is employed. Such function has been employed successfully in a number of studies involving safety assessment of structural integrity [Shiraishi et al. 1984].

A computer program has been developed for this module. Although this program is designed to filter out inconsistencies in the condition ratings, it can also be used to train new inspectors or to assist a bridge inspector in performing bridge inspection. Furthermore, it can be used to predict the condition rating of a bridge as a result of certain improvement activities. A description of this module can be found in Volume 2 of the final report [Tee et al. 1989].

#### 2.4 Bridge Traffic Safety Evaluation Module

Traffic safety can be one of the factors for recommending bridge improvement activities. Bridge traffic safety can be affected by many factors and subjective judgments are often made to assess it. This module allows the bridge inspector to translate their subjective judgments on bridge traffic safety into a quantifiable value. The overall traffic safety rating of a bridge hinges on the inspector's assessment of the importance of the safety

evaluation factors considered and the actual safety deficiencies of the components of a bridge. In order to assist inspectors making consistent judgments in evaluating traffic safety level of the bridges, an interactive computer program was developed. In the program, the bridge inspector is asked to input word ratings for the bridge components associated with traffic safety while the program computes a "bridge safety index" based on fuzzy sets principles [Zimmermann 1988]. The resulting value is used as an input to the ranking and optimization programs. In the ranking program, the index is converted to a ranking score by using the utility function of the bridge traffic safety index. In the optimization program, the index is used to modify the benefit of a bridge activity.

The safety evaluation model was developed on the basis of accident records of seventy-two (72) bridges which were identified by the district bridge inspectors as bridges where accidents may potentially occur. Bridge and approach roadway profile drawing sheets were also examined to find a general idea of the nature of accidents at these bridges and to verify whether the effects of the identified factors vary significantly from one bridge site to another. The weight of each of the factors ( $w_j$ ) was subsequently assessed through a questionnaire survey of the district bridge inspectors and bridge inspectors at the central office of INDOT.

During bridge inspection, each of the safety factors can be assigned a safety rating depending upon specific conditions of the bridge. The rating may be one of the following terms: very critical, critical, moderately critical (or moderately not critical), not critical, and highly not critical. The weights ( $w_i$ ) and ratings ( $r_i$ ) of all the factors can then be combined using the following equation to obtain the average rating ( $\bar{r}$ ) or the bridge safety

index.

$$\bar{r} = \frac{\sum_{i=0}^n w_i \times r_i}{\sum_{i=0}^n w_i}$$

Figure 2.2 shows a sample input and output of the bridge safety index computation package. As long as the weights are determined upon consensus of bridge inspection engineers, this computer program can be modified to include other factors not listed in Figure 2.2. The development of this module and the details of analyses are presented in Volume 3 of the final report [Murthy and Sinha 1989].

## 2.5 Improvement Activity Identification Module

This module would help the bridge manager to identify appropriate improvement activities and their code numbers, based on the evaluation of physical deficiencies. It is intended to provide a set of rules to select improvement alternatives. At present this module is not in existence and the alternatives are suggested by bridge inspectors in the SIA report.

Severity and extent of distresses present at the bridge structure call for specific types of improvement. In order to develop a computerized improvement alternative selection process, it is necessary to develop distress-improvement relationships by highway type, condition rating, and traffic volume. For this purpose, a data base must be created that can accumulate the information of all improvement activities performed for each bridge in the system over a period of time. The improvement activity recording and

Safety Rating of Bridge I74-6-4417D (WBL)

STRUCTURE NO: I74-6-4417D (WBL)	
CONTRIBUTING FACTORS	SAFETY RATING
<b>BRIDGE RELATED FACTORS</b>	
Roadway width	moderately critical
Relative roadway width	moderately critical
Shoulder width	critical
Shoulder width reduction	critical
Vertical clearance	not applicable
Approach guardrails and bridge rails	not critical
<b>APPROACH ROADWAY FACTORS</b>	
Approach sight distance	not critical
Approach roadway curvature	not critical
Approach gradient	not critical
<b>ENVIRONMENTAL FACTORS</b>	
Volume/capacity ratio	moderately critical
Percentage of trucks	moderately critical
Lighting, signing and delineation	not critical
Presence of nearby ramps, merges or intersections	not present
Presence of nearby lane drops or pavement transitions	not present

Bridge Safety Index estimated by the model = 3.27

Figure 2.2 Sample Input and Output from the Bridge Traffic Safety Evaluation Model

monitoring module based on the activity history data base (see Figure 2.1) would serve as the data bank for future analyses. At present some information has been developed on the types of improvement activities that may be recommended at certain condition ratings, as discussed in Volume 5 [Saito and Sinha 1989b].

The bridge manager is required to choose appropriate alternatives along with proper code numbers. In addition, this module should provide the bridge manager to estimate the effect of improvement alternatives on bridge component condition ratings and bridge life. Physical effectiveness tables developed for this module in Volume 5 [Saito and Sinha 1989b] are the results of the consensus of the bridge inspectors and managers achieved through a Delphi process. Table 2.2 shows a list of sample improvement activities for bridge decks. The table shows estimated effectiveness of the activities in terms of the increase in the overall component condition rating and the number of years possibly added to the remaining service life of the bridge. Effectiveness of an alternative is expressed by the average value and standard deviation. This information may be used in the prioritization process for ranking the alternatives projects. It is, however, absolutely necessary in the optimization procedure.

## 2.6 Impact Identification Module

Structurally deficient and/or functionally obsolete bridges would affect three broad groups: the highway agency, the highway user, and the surrounding community. For the highway agency, the effect of a structurally deficient bridge would be in terms of immediate investment in upgrading the bridge. For the highway user, the effect would be a long detour distance and extra travel

Table 2.2 Effectiveness of Deck Rehabilitation Alternatives on Condition Rating and Remaining Service Life (Mean Values)

Activity Type	Word Rating	Numeric Condition Rating		Increase in Service Life in Years			Chance of Recommendation (%)
		Before	After	Change	Minimum	Average	
Deck Replacement	V. Good	N.A.	N.A.		N.A.	N.A.	0
	Good	N.A.	N.A.		N.A.	N.A.	0
	Fair	8	4	4	16	21	0
	Poor	8	5	3	16	21	100
Deck Reconstruction	V. Good	N.A.	N.A.		N.A.	N.A.	0
	Good	7	3	3	12	17	0
	Fair	7	3	3	11	16	60
	Poor	7	4	3	10	15	100
Deck Patching	V. Good	N.A.	N.A.		N.A.	N.A.	0
	Good	7	1	5	7	8	60
	Fair	6	1	4	5	7	90
	Poor	6	2	3	5	7	100
	V. Poor	6	3	3	4	6	90

Notes: \* N.A. - Not applicable, meaning that inspector would rarely recommend this activity when condition rating is in the given level.

\* Percentage of the chance of recommendation was rounded to the nearest 10s.

time or it may be an increased potential for traffic accidents on detour roads. Traveling on unfamiliar local roads may increase distraction and fatigue for the driver. The third group affected would be the residents of the community on detour routes. For these people, the effect would be the annoyance created by a sudden surge of traffic foreign to the community. Since a bridge rehabilitation or a replacement often lasts for a long time, the effect would be long-lasting. Furthermore, it may happen that roadways designated as detour routes were not designed for a large number of heavy commercial trucks. Therefore, the residents on detour routes may suffer from not only the increase in accident potential but also the deterioration of their infrastructure. A bridge closure can also affect the community in which a deteriorated bridge is located. School bus operations in the surrounding area can be disrupted if load posting is made, and commuting patterns of the nearby communities may have to be changed. In addition, business establishments located in the vicinity of an deficient bridge can also be adversely affected.

The impact identification module would help the bridge manager to identify types and magnitudes of various impacts and to translate qualitative and quantitative effects into either monetary form or subjective rating indices. Details for estimating agency costs for bridge replacement, rehabilitation, and maintenance costs can be found in Volume 4 of the final report [Saito and Sinha 1989a]. The estimated detour length is suggested as a substitute factor to measure the impact on the highway user and the surrounding community. Procedures can be developed for estimating detailed user costs and impacts on surrounding communities.

## 2.7 Project Selection Module

The project selection module would not be a single computer package;

rather, it is a group of decision-making tools. There are three sub-modules, each sub-module is developed for a particular purpose. The sub-modules can be used singly or together to select and program a set of maintenance, rehabilitation, and replacement alternatives. The three sub-modules are:

1. Life cycle costing sub-module
2. Ranking sub-module
3. Optimization sub-module

All maintenance, rehabilitation, and replacement options can be included in the ranking and optimization of bridge projects. However, it is suggested that at present the bridges which would receive only routine maintenance be identified on the basis of condition rating and that the determination of specific routine maintenance activities be left to the Operations Division or districts. The project selection module of the proposed IBMS would be aimed at determining when to rehabilitate or replace.

The life cycle cost analysis sub-module would be used to find the most economic option at a bridge site based on the equivalent uniform annual cost for perpetual service approach. The projects thus selected can then be ranked using the ranking module. However, if the economic desirability is the only objective to be considered, the individual projects at various sites can be compared using the least life cycle cost approach and a priority list can be prepared. Details of the life-cycle cost analysis are discussed in Volume 4 of the final report [Saito and Sinha 1989a].

The ranking sub-module would be used to compare bridge projects on the basis of objectives, in addition to economic desirability. Results of the

life-cycle cost sub-module would thus be combined with bridge traffic safety indices, structural conditions, remaining service lives, community impact indices, and other factors. It should be noted, however, that ranking, by nature, may not give a statewide optimal solution. However, the list of ranked bridges can allow the bridge manager to identify initially which bridge projects may be placed in the following programming period. One advantage of ranking over optimization is that the ranking procedure is more transparent than the optimization program. Hierarchy of items or weights of items can be re-evaluated readily if final ranking is not acceptable to the bridge manager. The development of the proposed ranking procedure is given in Volume 5 of the final report [Saito and Sinha 1989b].

The optimization sub-module is the most complex procedure of the proposed project selection module. The optimization sub-module would be capable of testing the effects of various combinations of fiscal and other constraints upon the selection of bridge projects. A dynamic programming technique would be used in the optimization process. Bridge deterioration prediction curves are integrated in the model and a Markovian analysis is included to update condition ratings of bridges in consecutive programming years. The development of the optimization sub-module and a detailed discussion of this topic are found in Volume 6 of the final report [Jiang and Sinha 1989].

#### 2.7.1 Life Cycle Costing Sub-Module

For a highway agency, bridges are a long-term multi-year investment. Throughout its useful life, a bridge requires periodic maintenance and occasional rehabilitation. Especially the deterioration of bridge decks triggers most of rehabilitation works, probably because bridge decks are the most

immediate bridge structure component which is exposed to traffic and climatic changes such as snow and rain. As a bridge eventually approaches the end of its useful life, it is destined to replacement. Bridge costs are therefore a series of costs for maintenance, rehabilitation, and replacement, which may extend far into the future. This series of improvement actions for a bridge can be called as a life cycle activity profile [Hudson et al. 1987; Hyman and Hughes 1983].

Another type of cost associated with bridges is the user costs. These costs are attributable to a functional deficiency of a bridge, such as a load posting or clearance restriction. These functional deficiencies may cause higher vehicle operating costs because of detours, lost travel time, and higher accident rates. In the proposed bridge management system for Indiana, the user costs are not explicitly considered at this stage. It is, however, indirectly included in subjective community impact evaluation.

#### 2.7.2 Defining Life Cycle Activity Profiles.

In order to perform a life cycle cost analysis, it is necessary to construct a life-cycle activity profile. Life cycle activity profiles can be developed based on the knowledge of bridge history and bridge deterioration curves. The cost profile can provide a good estimate of expected future costs although it is unlikely that the amount and timing of future expenditures will exactly follow the projected profile. Unique identification codes can be assigned to improvement activities so that cost information can be automatically extracted from the data base. If precise cost estimates are available, they can be input to the life-cycle cost analysis program through an interactive session. Otherwise, default values included in the economic analysis

program can be used.

Two basic pieces of information must accompany each improvement activity: cost (either unit cost or total cost) and timing of implementation. A detailed cost and timing analysis of bridge maintenance, rehabilitation and replacement activities was conducted in the present study. The information on cost and timing is included in Volume 4 of this report. The conversion of life cycle costs of bridge improvement activities into costs of common terms follows a standard procedure [Grant et al. 1976]. Due to great uncertainty associated with inflation [Lee and Grant 1965], it is not recommended for inclusion in bridge economy study.

#### 2.7.3 Use of Equivalent Uniform Annual Cost.

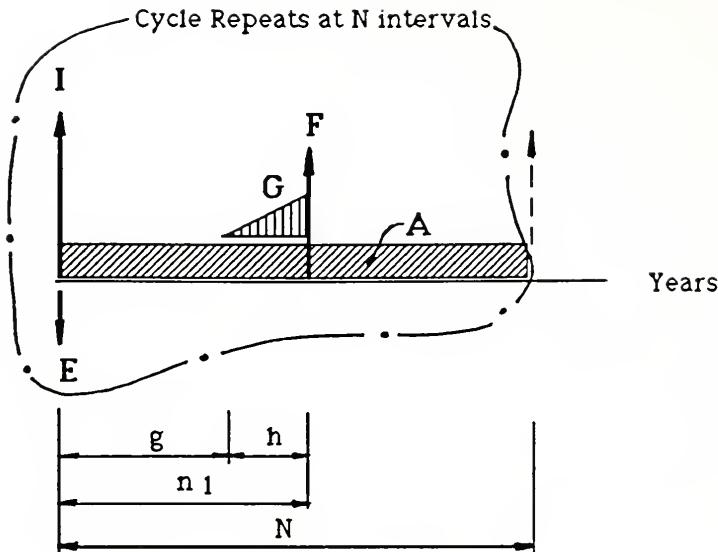
To compare a non-uniform series of costs, it is necessary to express costs in common terms. One way to do this is to express them in an equivalent uniform series of annual payments often referred to as equivalent uniform annual cost (EUAC). Equivalent uniform annual cost method will give answers consistent with present worth analysis, provided service lives are same for the alternatives. Technically, when only agency costs are considered for life cycle analysis, the performance of compared bridges must remain the same [FHWA 1987]. Therefore, if alternate options for a single bridge are compared to determine the least cost option (project level comparison), this assumption can be accepted. However, in order to compare projects for different bridges (network level comparison), the EUAC can not be the only factor for comparison, because individual bridges are different in many aspects such as bridge size and amount of traffic they serve. In this study, a weighing factor was employed to make the bridge life cycle costs commensurable. The fac-

tor is the ratio of annual traffic on the bridge to the EUAC. This factor gives the number of vehicles served by each dollar that is expected to be spent each year. Another approach can be to take the deck area as a normalizing factor so that large bridges do not end up being in a deferred category.

#### 2.7.4 Computing Equivalent Uniform Annual Cost.

Once a life cycle activity profile is established and expected costs for the planned activities are estimated, the uniform annual cost for this profile can be computed. Simple cases are used to explain the procedures. Figure 2.3 shows the activity profile and a general formula to compute EUAC for a replacement option. All future maintenance, rehabilitation, and replacement expenditure and the salvage value of the bridge are converted to a present value by multiplying appropriate factors (single payment present worth factor, uniform series present worth factor, and uniform gradient series present worth factor) for a given discount rate and life cycle. This present worth of all activity costs incurred during the life cycle is then expected to be spent periodically at an interval of a life cycle. The present worth of these periodic amounts can be aggregated to a total present worth of cash flows in perpetuity by multiplying with the appropriate perpetual series present worth factor. The EUAC in perpetuity can then be obtained by multiplying the aggregated present worth amount by the discount rate.

When maintenance and rehabilitation options are chosen as an immediate action, the bridge replacement work is actually deferred. Figure 2.4 shows a possible activity profile for an immediate rehabilitation case. In this case, the service life of the bridge is extended by M years and the bridge will have to be replaced at the end of M years. Hence, the present worth of replacement

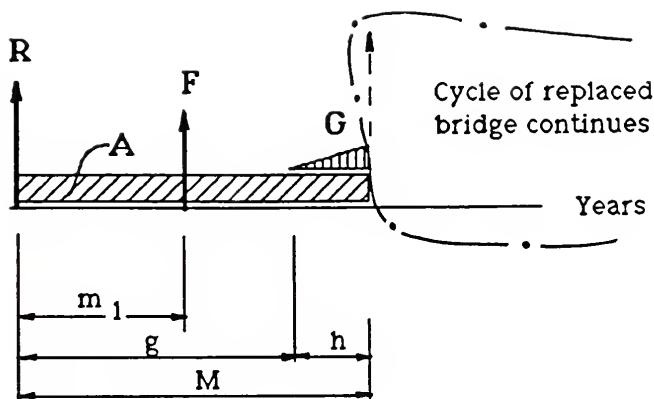


$$\begin{aligned}
 \text{EUAC}_{\text{replacement}} = & \left\{ \left[ I - E + G(\text{GSPWF}_{i,h+1})(\text{SPPWF}_{i,g-1}) + F(\text{SPPWF}_{i,n_1}) \right. \right. \\
 & \left. \left. + A(\text{USPWF}_{i,N}) \right] \right\} (\text{PSPWF}_{i,N}) i
 \end{aligned}$$

where

- I = initial replacement cost
- F = future rehabilitation cost
- A = annual maintenance cost
- G = gradient series of maintenance cost increase due to progressive deterioration
- E = salvage value of existing structure
- g = time passed before the beginning of uniform gradient series of maintenance cost increase
- h = duration of uniform gradient series maintenance cost increase
- $n_1$  = time passed before the future rehabilitation
- N = life of replaced new bridge
- i = discount rate
- SPPWF = single payment present worth factor
- USPWF = uniform series present worth factor
- GSPWF = gradient series present worth factor
- PSPWF = perpetual series present worth factor

Figure 2.3 Computation of Perpetual EUAC for a Replacement Option



$$\begin{aligned}
 \text{EUAC}_{\text{rehabilitation in perpetuity}} &= [(\text{Present Worth of Periodic Replacement Costs})(\text{SPPWF}_{i,M}) \\
 &\quad + (\text{Present Worth of Costs during the Extended Life})] \\
 &= [(\text{Present Worth of Periodic Replacement Costs})(\text{SPPWF}_{i,M}) + R \\
 &\quad + F(\text{SPPWF}_{i,m_1}) + G(\text{GSPWF}_{i,h+1})(\text{SPPWF}_{i,g-1}) + A(\text{USPWF}_{i,M})]i
 \end{aligned}$$

where

$R$  = initial rehabilitation cost

$F$  = future rehabilitation cost

$A$  = annual maintenance cost

$G$  = gradient series of maintenance cost  
increase due to progressive deterioration

$E$  = salvage value of existing structure

$g$  = time passed before the beginning of uniform  
gradient series of maintenance cost increase

$h$  = duration of uniform gradient series  
maintenance cost increase

$m_1$  = time passed before the future rehabilitation

$M$  = extended life of the existing structure

$i$  = discount rate

$\text{SPPWF}$  = single payment present worth factor

$\text{USPWF}$  = uniform series present worth factor

$\text{GSPWF}$  = gradient series present worth factor

Figure 2.4 Computation of Perpetual EUAC for a Rehabilitation Option

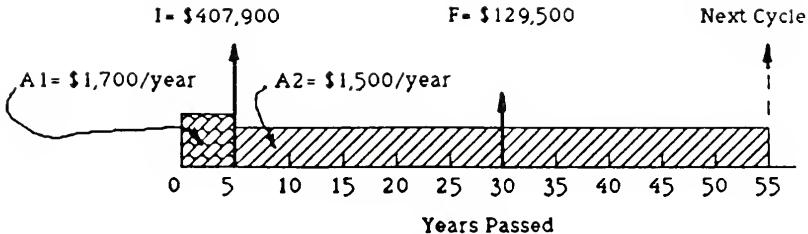
costs, aggregated at the beginning of the first replacement cycle, should be properly discounted to the present time by SPPWF and added to the present worth of all maintenance and rehabilitation costs incurred during M years. Salvage values can be included, if desired. However, salvage value is unlikely to have a significant impact on the outcome of an economic analysis [Wonsiewcz 1988] and it seldom affects the ranking of bridges significantly.

#### 2.7.4.1 Sample Application

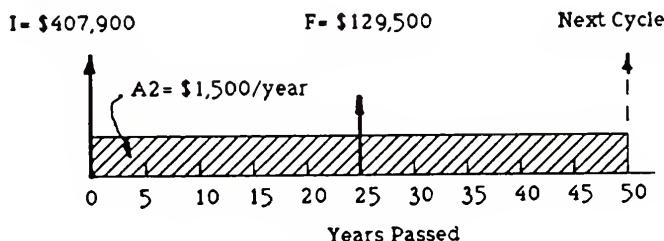
In this case, a bridge replacement option is being considered with two different timings. The bridge is in poor condition, and an immediate replacement is desirable. However, if necessary for financial and other reasons, the replacement can be deferred for 5 years. Figure 2.5 illustrates the life cycle activity profiles and the computational procedure to obtain the equivalent uniform annual cost for perpetual service. The zero date is the beginning of the programming year. The cash flow diagrams in the figure show the timings and costs of replacement and maintenance works. The salvage value of the existing bridge is assumed to be nil. As shown in the example, the bridge would still need routine maintenance until it is replaced. The economic gain of not replacing the bridge immediately is  $-(25,938 - 20,691)$  or \$5,247 per year in perpetuity. If functionally adequate and if structurally within acceptable limit, the bridge replacement can be deferred for five more years and the funds can be used for more critical needs.

#### 2.8 Ranking Sub-Module

A list of ranked bridges can give a prioritized order of bridges in need of improvements. Rank ordering bridge projects can help to reexamine those bridges which are on the border of budget limitations.



$$\begin{aligned}
 \text{EUAC}_1 &= 0.05[1,700(\text{USPWF}_{0.05,5}) + (\text{Present Worth of Deferred Periodic} \\
 &\quad \text{Replacement Costs at the Time of 1st Replacement})(\text{SPPWF}_{0.05,5})] \\
 &= 0.05[1,700(\text{USPWF}_{0.05,5}) + (\text{PSPWF}_{0.05,50})\{407,900 \\
 &\quad + 129,500(\text{SPPWF}_{0.05,25}) + 1,500(\text{USPWF}_{0.05,50})\}(\text{SPPWF}_{0.05,5})] \\
 &= \$20,691
 \end{aligned}$$



$$\begin{aligned}
 \text{EUAC}_0 &= 0.05[\text{Present Worth of Periodic Replacement Costs}] \\
 &= 0.05[(\text{PSPWF}_{0.05,50})\{407,900 + 129,500(\text{SPPWF}_{0.05,25}) \\
 &\quad + 15,00 (\text{USPWF}_{0.05,50})\}] \\
 &= \$25,938
 \end{aligned}$$

Legend:

- $A_1$  = Maintenance cost during deferment
- $A_2$  = Maintenance cost after replacement
- $F$  = Deck reconstruction and overlay cost
- $I$  = Bridge replacement cost
- $\text{EUAC}_1$  = Equivalent uniform annual costs  
in perpetuity for deferred  
replacement option
- $\text{EUAC}_0$  = Equivalent uniform annual costs  
in perpetuity for immediate  
replacement option

Figure 2.5 Sample Calculation for a Single Bridge with Immediate and Deferred Replacement Options

As a bridge ranking index, FHWA developed the sufficiency rating (SR) ranges from 0 to 100. This index is computed using structural condition ratings of bridge components and other information such as serviceability and essentiality of bridges [FHWA 1979]. This rating is used to determine whether bridges are eligible for funding under the Federal Highway Bridge Replacement and Rehabilitation Program (HBRRP). A nationwide questionnaire survey of state highway agencies conducted in the present study showed that the Sufficiency Rating index is often used for separating bridges into either the rehabilitation or the replacement category, to satisfy the federal funding requirement [Saito and Sinha 1987]. In actual priority setting process at the state level, the SR index plays relatively a minor role. Although the SR index approach may be an acceptable method to allocate bridge improvement fundings at the national level, other methods of calculating ranking index can be defined at the state level to meet the particular needs and level of service goals of a state agency. FHWA encourages states to develop methods which would meet state programming needs. For instance, North Carolina developed a bridge management program using the level of service as a major decision factor where bridge condition ratings played a minor role [Johnston and Zia 1985]. In the present study, a new ranking index is used; however, the sufficiency rating is retained as a reference in the ranking output.

#### 2.8.1 Indiana BMS Ranking Index

The ranking method for the proposed IBMS is based on a utility concept. That is, the model ranking system reflects the effectiveness criteria of bridge improvement alternatives as perceived by bridge inspectors and programmers. The approach used to do the ranking computations is known as the analytic hierarchy process (AHP). This process was developed by Saaty [1980]

and it helps the decision-maker reduce the ranking problem to a sequence of pairwise comparisons of properly identified decision factors and criteria. The IBMS ranking method modified the AHP procedure by including utility curves in the ranking process. This method is an improvement to the successive sub-setting technique which was developed at Purdue to rank bridge projects [Harness and Sinha 1983]. The use of the analytic hierarchy process makes it possible to rank a large number of bridge projects; the successive subsetting technique was meant for a small number of bridges for which graphical subsetting technique could be applied.

The analytic hierarchy approach (AHP) allows the decision-maker to stratify criteria into several clusters. For instance, the first level of hierarchy of bridge ranking may be to achieve the efficient use of bridge funds. At the second level, there may be objectives such as maximization of bridge remaining service life, maximization of traffic safety, and maximization of the level of service. Under each objective, the decision-maker selects attributes which can be used to measure the level of contribution of bridge improvement to the objective. Bridges are evaluated with respect to these attributes and appropriate expected utility is computed. In order to deal with a larger number of projects, it is necessary to have appropriate evaluation functions and these functions are called utility functions. Figure 2.6 shows a general structure of the analytic hierarchy process.

Utility curves can reflect the value judgment of inspectors and programmers for implementing certain improvement options to ameliorate existing distresses and bring the bridge back to an acceptable condition level. In order to construct utility curves, pair-wise judgments are first made among the levels of individual evaluation attributes by using a one-to-nine scaling system

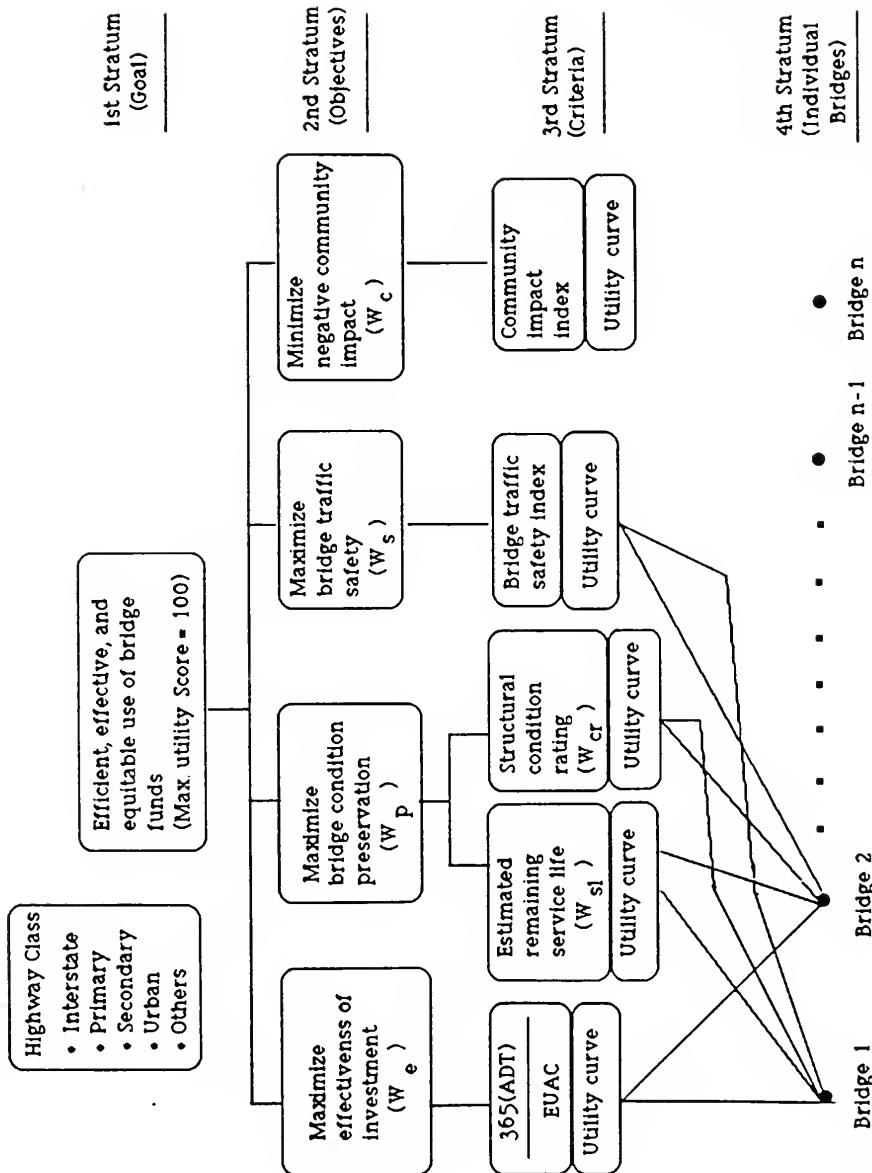


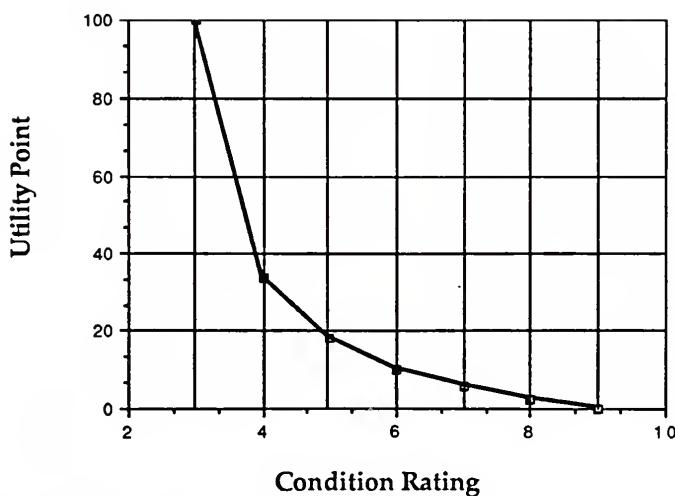
Figure 2.6 Recommended Four-Strata Default Hierarchy for IBMS

Condition Rating = Min (Superstructure, Substructure)

Condition Rating	Condition Rating					Eigenvector	Utility Point
	3	4	5	6	7		
3	1	5	7	8	9	1.0000	100.00
4	1/5	1	3	4	5	0.3375	33.75
5	1/7	1/3	1	3	4	0.1850	18.50
6	1/8	1/4	1/3	1	3	0.1035	10.35
7	1/9	1/5	1/4	1/3	1	0.0597	5.97

$$\lambda_{\max} = 5.35 \quad C.I. = 0.09 \quad R.I. = 1.12 \quad C.R. = 0.08 < 0.10$$

(a) Pairwise Comparison Matrix, Eigenvector, and Utility Points



(b) Utility Curve for Condition Rating

Figure 2.7. Pairwise Comparison Matrix and Utility Curve for Condition Rating

[Saaty 1980]. Pair-wise judgments are placed in a matrix called a reciprocal matrix and a set of scaling values is produced by the eigenvalue approach [Saaty 1980]. Figure 2.7 illustrates this process using condition rating. In the example, the levels of condition rating are compared in pairs and weights are given using the one-to-nine scale.

After computing utility points of each project with respect to the evaluation attributes under the criteria, relative weights of the criteria are multiplied to obtain an aggregate utility point of the project. Ranking of bridge projects can be done by using this combined utility points. Table 2.3 shows a list of information which can be an output from this ranking method. Bridge projects can be ranked in terms of each criterion, and trade-offs between criteria can then be examined.

## 2.9 Optimization Sub-Module

In the present study, an optimization procedure using a combination of integer programming and dynamic programming techniques is used to select optimally rehabilitation and replacement projects. Integer programming is used to maximize the statewide bridge system effectiveness in each programming period subject to budget and other constraints. Dynamic programming is then used to select an optimal policy which maximizes the system effectiveness over a given planning horizon by comparing the results of integer programming. In one version of the optimization model, the system effectiveness is represented by the sum of increased serviceability of individual bridges due to improvement activities. The increased serviceability is measured by the area surrounded by the current bridge deterioration curve and the new deterioration curve resulting from the improvement. This area is weighted by traffic

Table 2.3 Suggested Items to be Printed in the Bridge Rank Report

1. Ranking Index by Total Utility Point
2. Bridge Identification
  - i. Structure number
  - ii. Highway type (Interstate or Other Highways)
  - iii. Route number
  - iv. County number
  - v. District number
  - vi. Mileage post
3. Utility Points by Selection Objectives (As requested)
4. Basic Bridge Attributes
  - i. Bridge type
  - ii. Year of last construction
  - iii. Structural length (ft)
  - iv. Clear deck width (ft)
  - v. Deck area (sq ft)
  - vi. Vertical underclearance (ft)
  - vii. Vertical overclearance (ft)
5. Bridge Condition Information
  - i. Deck condition rating
  - ii. Superstructure condition rating
  - iii. Substructure condition rating
  - iv. Approach roadway alignment
  - v. Waterway adequacy
6. Bridge Appraisal Type Information
  - i. Load capacity
  - ii. Remaining service life if nothing is done
    - a. Deck
    - b. Superstructure
    - c. Substructure
  - iii. Bridge traffic safety index
7. Improvement Information
  - i. Replacement (P), Rehabilitation (R), or Maintenance (M)
  - ii. Estimates of expected repair costs
    - a. Next capital investment
    - b. Annualized life cycle cost
  - iii. Proposed year of repair activities

volume, traffic safety, and community impact factors. In another version of the optimization model, the utility values generated by the Ranking Sub-Module are used, and the objective function maximizes the systemwide gain in utility. The only difference between the two versions is in the objective function. However, because the second version combines ranking and optimization techniques into one interacting model, it is recommended that this version be used in IBMS for selecting optimal set of bridge projects.

Integer programming has been widely used in decision making-problems. In this technique the variables have a value of either zero (0) or one (1). A project is selected if a decision variable corresponding to that option results in one, and it is not selected when the variable results in zero. Dynamic programming is a particular approach to optimization. It does not involve a specific algorithm in the sense that simplex algorithm is a well-defined set of rules for solving a linear programming problem. Instead, dynamic programming is a way of looking at a problem which may contain a large number of interrelated decision variables so that the problem is regarded as if it consisted of a sequence of problems. Ideally, the dynamic programming approach transforms an n-variable problem into a series of n one-variable problems. Whenever this transformation is possible, the transformed problem usually requires much less computational effort than the original problem. An important advantage of dynamic programming is that it determines absolute (global) maxima or minima rather than relative (local) optima [Cooper and Cooper 1981]. The principle of optimality assures that dynamic programming results in not only the optimal solution of a problem, but also the optimal solution of subproblems [Cooper and Cooper 1981].

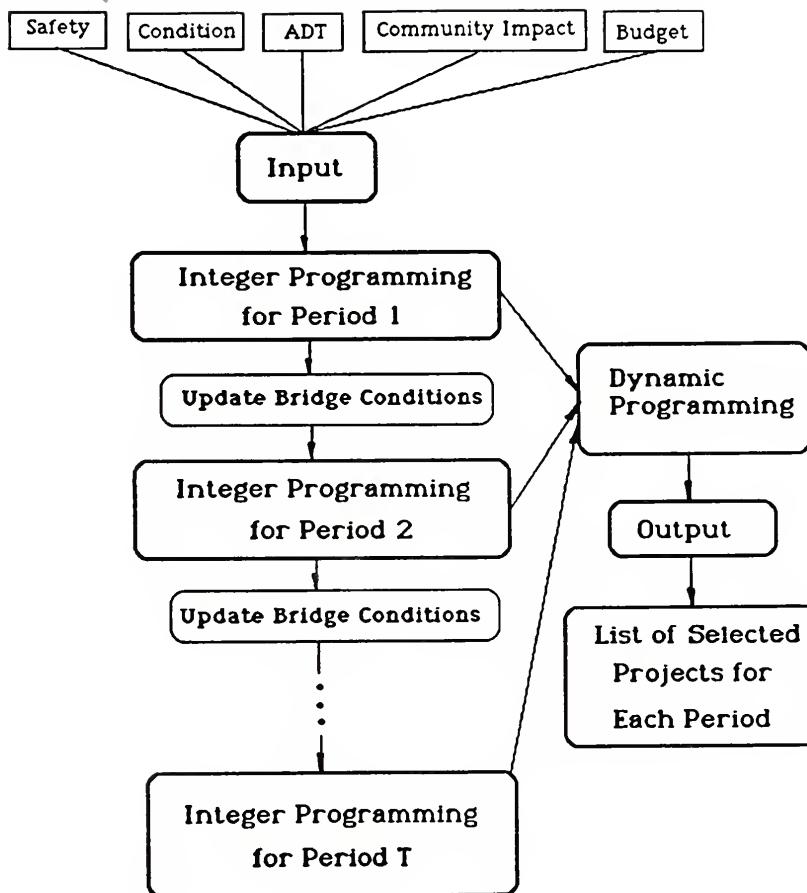


Figure 2.8 Flow Chart of the Optimization Model

A bridge can be considered to progress through a series of consecutive stages and each programming year can be assumed to coincide with a stage. At each stage, the system can be described by states such as funds available and bridge condition. At each stage, decisions must be made. The decision such as funding allocation and project selection depend only on the current stage and state; the past history of the system is of no importance.

Figure 2.8 shows a flow chart of the optimization programming for T periods (each consisting of two programming years) for a planning horizon, say 6 years from now. When selecting projects for a given budget, the model maximizes systemwide effectiveness (or utility gain) and the system undergoes a transformation to the next stage. The output lists the projects selected for rehabilitation and replacement for each period for different scenarios of federal and state fund levels. The projects selected can be prioritized by project type as well as by district for each year under each funding scenario.

#### 2.9.1 Deterioration Curves.

The deterioration curve gives a predicted condition rating of a bridge component with respect to bridge age. Deterioration curves are used to compute the effectiveness of improvement alternatives in one version of the optimization model. They are also used to weigh the objective function so that an improvement is selected at a point when the deterioration rate is the steepest. They were developed for groups of bridges identified by bridge type (concrete or steel) and highway type (interstate or other state highways). A third order polynomial regression function was used to develop deterioration curves. The general form of the third-order polynomial function is given below:

$$Y(t) = A + Bt + Ct^2 + Dt^3$$

where  $Y(t)$  is average condition rating for a particular bridge group;  $A$ ,  $B$ ,  $C$ , and  $D$  are regression coefficients; and  $t$  is average bridge age for the group. Figure 2.9 gives deterioration curves for concrete bridge components on non-interstate highways (other state highways).

#### 2.9.2 Markovian Transition Probabilities.

In this study, a Markovian analysis is used to update condition ratings for the next stage in the dynamic programming. A Markovian analysis is a procedure that can be used to describe the behavior of a system in a dynamic situation and it is suited for a dynamic programming application. When a bridge is not selected for improvement in the current period, its deck condition either stays in the same condition rating level or gets worse in the next stage. This transition of condition rating is predicted for the next stage using the condition rating of the current period. A coefficient of a transition matrix,  $p_{ij}$ , indicates the probability of a bridge component moving from condition rating  $i$  to condition rating  $j$  during a programming period. In this study, a transition matrix was developed for every six year interval of bridge age to make the matrix time homogeneous using the actual bridge condition rating data between 1978 and 1986. The data from this period included bridges with an age range of 1 to 60 years.

The advantage of using the Markov chain is that the change in the next period is only affected by the condition state of the current period. When a regression curve is used to estimate the condition rating of a bridge at a certain bridge age, all bridges which are included in the group will have the same condition rating irrespective of what values actual condition ratings

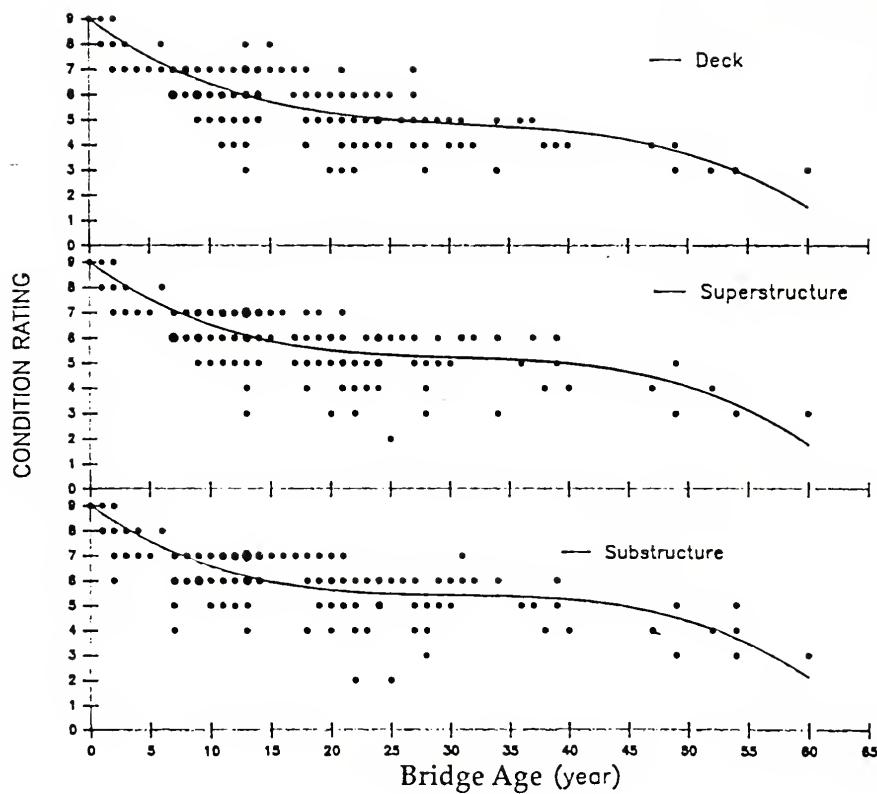


Figure 2.9 Performance Curves of Concrete Bridge Components on Other State Highways

were. However, if the Markov transition matrix is used, the actual condition rating does not need to be adjusted to the expected value. Deterioration during the next stage would follow the last condition rating.

#### 2.10 Activity Recording & Monitoring Module

Most of the data needed for various analyses are available at InDOT. However, they are not well coordinated or organized at present. For example, replacement and rehabilitation records are now kept in the bridge structure record, but this record only lists a broad category of tasks, date of implementation, and type of contract, along with the basic information such as structure number, contract number, and crossed facility. Cost data of rehabilitation and replacement works are stored in a separate data base for reporting unit costs to FHWA. This record, however, does not include maintenance history or maintenance cost. Force account maintenance activities are recorded by a program administered by the Maintenance Division. Accomplished maintenance activities are summarized from crew day cards by subdistrict. The current recording system makes it difficult to trace the maintenance history to individual bridges.

This module would be set up to keep track of maintenance, rehabilitation, and replacement of all bridges in the network and to accumulate historical data. Data from this module can be used to conduct statistical analyses on bridge improvement alternatives. The accumulated data on cost, timing, and sequence of bridge related activities can be used in the future to upgrade the project selection module of the proposed IBMS. Variables needed for future analyses may include date, type, cost, and effectiveness of improvement activities. To code improvement activities in the historical data base, the

same coding scheme as the one used for the improvement activity selection module should be used.

In order to incorporate bridge routine maintenance in the overall bridge management system, it is necessary to coordinate with the maintenance management program of the Maintenance Division. The information on bridge maintenance should be periodically entered from crew-day cards to the historical data file. Also, it should be required that maintenance crews record exact locations of bridges that have been worked on. Table 2.4 lists a set of information that unit foremen or other maintenance personnel should record in the crew-day card so as to make this module useful within the proposed IBMS. This module can be used also for checking the backlog of needed bridge maintenance activities.

#### 2.11 Reporting Module

Reports are the means of communication between the proposed IBMS and its various possible users. The reporting module is not a self-standing module isolated from the other modules and sub-modules, but it encompasses all components of the IBMS. Reports generated by this module are actually outputs from other modules and sub-modules. The following reports would be produced from the reporting module:

1. Bridge Condition Summary
2. Bridge Characteristics Summary
3. Maintenance Need and Backlog Summary
4. Improvement Activity Summary
5. Network Level Impact Summary

Table 2.4 Information Required for Bridge Routine Maintenance Monitoring

1. Bridge Identification
  - i. Bridge reference number
2. Maintenance Activity Information
  - i. Date of performing the activity
  - ii. Type of activity and activity code
  - iii. Manhours needed
  - iv. Amount of work in proper units

6. Life Cycle Cost Analysis Report
7. Priority Ranking Report
8. Optimal Activity Programming Summary
9. Budget Reports

In addition to the above new reports, the following existing reports are available:

1. The SIA reporting to FHWA
2. Annual inventory of bridges
3. Unit cost computation report
4. Overweight vehicle permit report

A brief discussion of the new reports is given below.

#### 2.11.1 Bridge Condition Summary

This report would provide a summary on the distribution of condition ratings of state-owned bridges. Summary statistics can be given by district, subdistrict, bridge type, age, functional class, level of ADT, and other grouping factors included in the data base.

#### 2.11.2 Bridge Characteristics Summary

This report would give summary statistics on bridge characteristics included in the IBMS to help the bridge manager to evaluate the current status of the state-owned bridges. Bridge characteristics may include variables such as bridge length, width, age, sufficiency rating, traffic safety index, bridge type and other characteristics included in the data base.

#### 2.11.3 Maintenance Need and Backlog Report

This report would give types and amounts of accomplished maintenance

activities and the backlog of needed maintenance. This report can be summarized by either district or subdistrict to help maintenance managers identify bridges which need immediate or future attention. The information can also be used by programmers in scheduling bridge improvement activities.

#### 2.11.4 Improvement Activity Summary

A summary report would be given for the types of improvement activities included in the proposed IBMS by using the data kept in the activity recording and monitoring module. An activity summary can be given for each bridge or for a group of bridges. The grouping can also be made by improvement activity type included in the IBMS and the sum total of estimated expenditures. This summary would help the bridge manager to estimate the amount of money needed to execute certain improvement activities.

#### 2.11.5 Network Level Impact Summary

This report would be designed to give a summary of potential impacts of bridge related activities including user costs and community impacts. At present, only a part of this report can be produced because the user costs and community impacts can not be explicitly determined.

#### 2.11.6 Life Cycle Cost Analysis Report

This report would give results of the life cycle cost analysis. A comparative summary can be made for a project level analysis, or a network level analysis. This report would help bridge managers to identify which bridges should be recommended for either maintenance, rehabilitation, or replacement.

#### 2.11.7 Priority Ranking Report

This report would give a list of bridges ranked by the ranking method proposed in the present study. Bridges can be ranked either by the total utility point or the utility point earned for each criterion. Besides the utility points, information such as bridge length, width, estimated cost, and improvement action can be listed as well as bridge number and location. This report, to be obtained by running the ranking sub-module, may not give an optimal solution to bridge project programming; however, the ranking list can be effectively used in the scheduling of projects.

#### 2.11.8 Optimal Activity Programming Summary

This report would give bridge projects selected by the optimization sub-module of the project selection module. It would list rehabilitation and replacement options by programming period in a given planning horizon. It would also give the estimates of improvement costs for individual bridges, the extent of federal and state funds used, and the location of selected projects by district.

#### 2.11.9 Budget Report

This report would be an aggregate summary on expected budget schedule to maintain the state bridge network at desired condition and safety levels. It would provide condition summaries and associated expenditure levels under various funding scenarios. Contents of this report would be the result of multiple runs of the optimization sub-module under different budget scenarios.

## CHAPTER THREE

### IBMS IMPLEMENTATION PROCEDURE

A discussion of the modules for the proposed IBMS has been given in the previous chapter. These modules would be used at different stages of IBMS. In this chapter, a discussion is presented as to when and how these modules can be used by bridge inspectors and other bridge managers in the selection of bridge projects within the constraints of available resources. Figure 3.1 illustrates the suggested IBMS implementation procedure. It also lists what types of reports can be produced at various stages. As shown in this figure, the overall procedure of the IBMS would not differ significantly from the existing practice, but it would make the process more systematic and efficient. The district inspectors would feed in information on condition rating, appraisal, proposed work, and the bridge management group at the central office would use them to select bridges for improvement. The proposed system would streamline the project selection process and provide the bridge managers a tool to create different programming schedules for various funding scenarios. The proposed IBMS especially emphasizes the consistency of input data stored in the database as well as the structure of bridge management system.

#### 3.1 Create Data Bases

Two separate data bases would be created for the IBMS: one for running the three sub-modules of the project selection module and the other for storing historical data monitoring all activities on individual bridges. The current SIA bridge data file is meant for the inventory of bridges and cul-

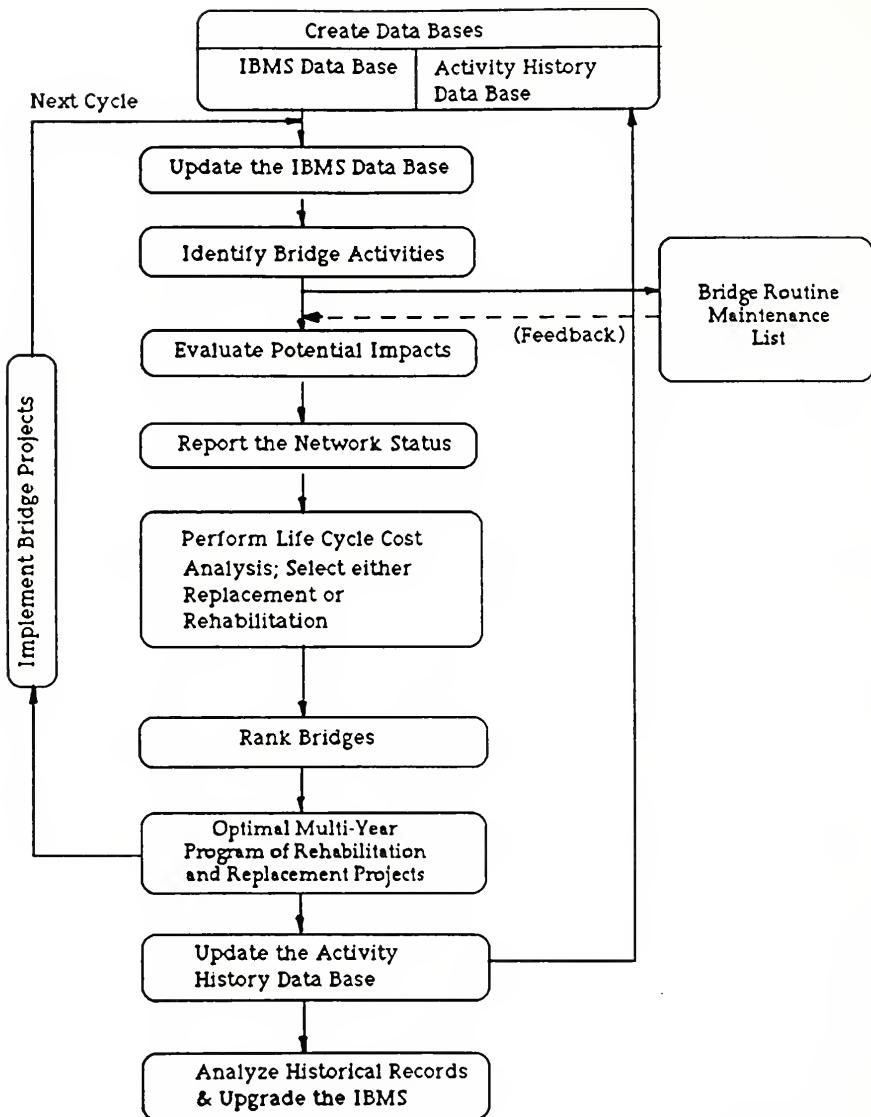


Figure 3.1 IBMS Implementation Procedure

verts in the state including those owned by counties and cities. However, the IBMS is aimed at managing only state-owned highway bridges. Hence, a new data base should be created containing only the records needed to manage the state-owned bridges and thus much computer cost and memory storage can be saved. Data items which were recommended for IBMS are found in Table 2.1. This data base would contain only the necessary data to implement the system.

Another new data base is needed to store historical records of construction, maintenance, and rehabilitation activities for individual bridges. This data base would become the core of the activity recording and monitoring module. Records would contain data such as type, amount, timing, and cost of each bridge work. This cumulative data would provide vital information for future analyses of bridge works and for continual updating of the proposed bridge management system.

### 3.2 Update the IBMS Data Base

Each bridge has to be inspected every other year to comply with the National Bridge Inventory program. Therefore, records of individual bridges are updated at least every other year. Any changes in the data base could be initiated by district bridge inspectors. The bridge inspector can take advantage of the following three modules of the IBMS in updating the bridge records: the condition rating assistance, traffic safety evaluation, and improvement activity identification modules.

The condition rating assistance module would help the inspector to assign appropriate ratings to bridge components. This would not be a mandatory process to be followed, but the inspector would be encouraged to consult the module for spot checking the consistency of his ratings. This module would be

especially helpful to train a new inspector so that he or she can develop a condition rating system commensurate with other inspectors in the state.

The safety evaluation module would help the inspector compute a bridge traffic safety index. This index is proposed to be used in the ranking and optimization procedures. Therefore, in creating the IBMS data base, all bridges must be evaluated for determining bridge safety indices. After the initial creation of the data base, only those bridges which have experienced some changes in the safety factors need to be updated. The safety index is a new item that may be added to the existing inspection program.

### 3.3 Identify Bridge Activities

The improvement activity identification module would help the inspector to identify appropriate categories of maintenance improvement activities and codings. In order to make the records commensurate with each other between different modules, it is necessary to use the consistent activity coding system. The inspector is asked to identify possible alternatives to improve the bridge condition according to the current design and operational standards. He or she would record the possible timing and extent of recommended activities in the inspection reports. The collection of the rest of the inspection data items would follow the instructions given in the SIA recording and coding guide [FHWA 1979, 1988] and other supplemental guidelines presented by the central office bridge inspection group. The district bridge inspectors would send the information on identified activities along with other data to the central office. All bridges except those requiring rehabilitation or replacement during the next 10 years would be sorted out by the IBMS computer program and the information sent to the Operations Support Division for maintenance

planning.

### 3.4 Evaluate Potential Impacts

At this stage of the IBMS, possible consequences of undertaking various alternatives including "do-nothing" would be assessed. The impact identification module is to be used here to estimate potential impacts in terms of agency cost, highway user cost, and community impact. As for agency cost, cost prediction models developed in the present study can be used. The impact on highway user cost as well as the impact on surrounding communities would be measured at present by a proxy value such as detour length in case of posting or closure. The detour length is one of the data items included in the SIA bridge records collected by the state. It can be periodically updated by district bridge inspectors taking into consideration of any changes in the possible detour routes near the deteriorated bridges. Results of this step become a part of the input data for the ranking and optimization sub-modules.

### 3.5 Report the Network Status

Once the BMS data base is completed and updating task is accomplished regularly, the status of bridges can be obtained at any time upon request. Four types of summary reports can be created whenever requested, because these are made by simply manipulating the IBMS data base. They include the present condition summary report, bridge characteristic summary report, improvement activity summary report, and network level impact summary report. Contents of these reports were discussed in the previous section.

### 3.6 Perform Life Cycle Cost Analysis

The objective of performing a life cycle cost analysis is to determine

which alternative should be selected for a particular bridge to incur the least life cycle cost to provide a particular level of service. The life cycle cost analysis can be used to select the most economic option for a particular bridge. The approach can also be used to compare projects at different bridge sites. For comparing the projects at different sites, the EUAC values are weighted by ADT to incorporate the variation in the level of service. A life cycle report can be produced for each bridge, for a group of bridges, or for the entire system. A life cycle activity profile would be set up by the bridge manager. Otherwise, default profiles would be assigned by the computer model.

### 3.7 Rank Bridges

The ranking sub-module of the IBMS is to be used when evaluating bridges with varying levels of service and a wide range of impacts. First, a set of decision factors would be selected by the programmer from a set of decision factors for which utility functions have been developed in the study. The bridge manager may develop a new hierarchical decision tree and determine their weights as the program is run. Otherwise, a default hierarchy would be selected. If a new factor is to be included, a utility function needs to be developed for that factor along with its relative weight with respect to the criteria to which the factor belongs.

Once the hierarchy is set, the ranking module would use it to compute total combined utility points as well as the utility points for each criterion. Bridges can be ranked by utility score of any decision criterion as well as by the total utility score. A priority ranking list is created from

this step.

### 3.8 Program Rehabilitation and Replacement Projects

In the proposed IBMS, an initial list of bridges requiring rehabilitation and replacement activities is to be prepared by the central office bridge management group on the basis of life-cycle costing and/or ranking sub-module. This list would be sent to the district offices for review and modification. The bridge management group would then adjust the selected projects taking into consideration feedbacks from the district offices. The optimization program would then be run at this point to determine the type and timing of activities to be performed on selected bridges. The optimization program could be run several times for comparison when various funding scenarios would have to be considered. From this step, a network improvement activity programming summary report and a budget report would be produced. A final activity programming schedule would then be sent to the HIP planning group for evaluation with other highway related projects. If any adjustments are requested by the HIP group, the optimization step will be repeated to meet the requirements set by the HIP group in the development of the final highway improvement program.

### 3.9 Update the Activity History Data Base

The second data base of the proposed IBMS is for recording and monitoring maintenance and improvement activities for individual bridges. This data base would consolidate activity records currently scattered in several files, either computerized or manual, into one single data base. Whenever an activity is completed on a bridge, necessary information about the work is to be recorded in this data base. Acquisition of maintenance records is to be

coordinated with the Operations Support Division of INDOT. Although this step is listed in the latter part of the implementation procedure in Figure 2.1, it can be invoked any time when the records need to be updated.

### 3.10 Analyze Historical Data and Update the IBMS

The proposed IBMS has all necessary elements to meet the requirements for programming bridge improvement works for inclusion in the biennial Highway Improvement Program. However, the components of this system would need periodic updating. The activity recording and monitoring module is to be used to accumulate necessary data for future analyses to improve the individual IBMS modules. For instance, at the initial stage of implementation, bridge improvement activities would be only broadly categorized into deck reconstruction, deck replacement, and bridge replacement. After several years of systematic data recording and analyses, sufficient information would be generated to have more specific activity groupings.

## CHAPTER FOUR

### ORGANIZATIONAL FRAMEWORK FOR THE IBMS

To improve the effectiveness of data collection, analysis and prioritization, and to facilitate communication between the central office and district offices, the formation of a bridge management group would be necessary. The bridge management group would reside in the Program Development Division of InDOT and it would be made up of two sub-groups, the bridge inspection sub-group and the bridge activity programming sub-group. The benefit of setting up such a group is discussed below by comparing the current bridge programming procedure with the proposed one.

#### 4.1 Current Bridge Project Programming

Figure 4.1 shows the flow of information in the current bridge programming procedure. The bridge inspection group at the central office is the core of the existing bridge management, because it works as a resource station for the district inspectors as well as the central record keeper. The bridge inspection group ensures that the districts adhere to their biennial bridge inspection schedule. Under the guidance of the bridge inspection group, the district bridge inspector carries out the scheduled inspection of the bridges within his jurisdiction. The inspector fills in the bridge inspection report at the bridge site. An inspection report contains blanks for information requested by Items 58 through 75 of the FHWA Recording and Coding guidelines [FHWA 1979], covering condition rating, appraisal, and proposed work, besides the general inventory records. The inspector writes down not only numerical ratings but also subjective word ratings such as good, fair and poor, when

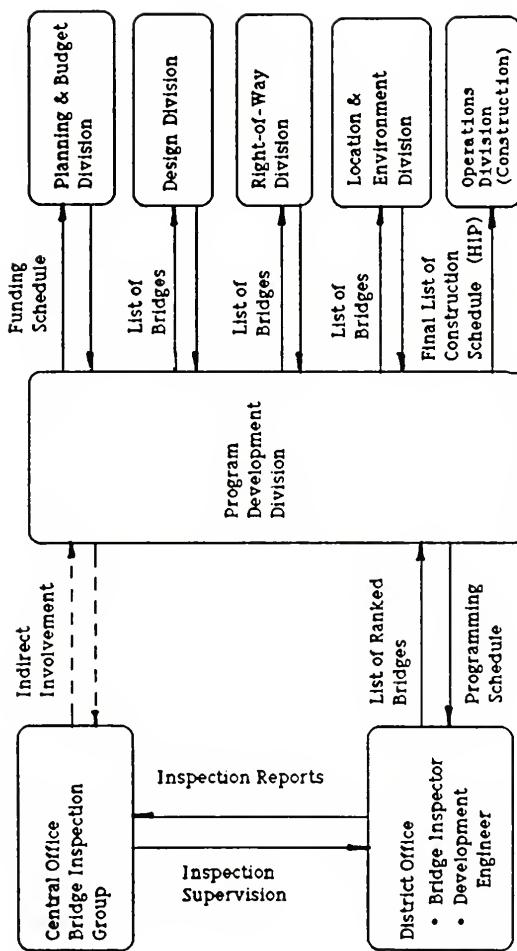


Figure 4.1 Flow of Information in the Project Programming Procedure as of 1988.

appropriate. The inspector lists proposed improvements with their recommended years of implementation. He may add verbal descriptions about the distresses he finds on the bridge structure and take photographs to supplement his observation. Inspection reports are then returned to the bridge inspection group of the central office for record keeping and coding into the SIA data base. If the district bridge inspector needs assistance in inspecting certain bridges, he requests an on-site inspection by the central office bridge inspectors.

Although the bridge inspection group at the central office plays a key role in data collection, the group is not directly involved in the actual programming of bridge projects. The selection of candidate bridge projects consists of a series of meetings between the district office and the programming group of the Program Development Division. The district bridge inspector prepares an initial list of ranked bridges requiring improvements upon consultation with the district development engineer under the supervision of the district engineer. After meetings and discussions with the inspectors from other districts and the central office programming group, the final set of bridges are selected for inclusion in the HIP. The program coordinator then consults with other INDOT divisions, such as the Planning and Budget Division, Design Division, Right-of-Way Division, and Location and Environment Division for their feed-backs about the feasibility of selecting particular bridges to be included in the next biennial Highway Improvement Program. After budgets are allocated, design drawings are prepared, environmental aspects are cleared, and right-of-way is purchased, if necessary, and the selected improvement projects are let for contract.

In the existing procedure, the prioritization process is initiated by the district bridge inspector. The advantage of this procedure is that the district inspector knows best about the bridges in his jurisdiction and thus can point out immediate needs. The disadvantage is that the district inspector makes decisions based upon his perception of the improvement need and it may not be consistent with inspectors in other districts. Consequently, the basic data may contain biased opinions. Furthermore, because no systematic procedure for priority setting exists at present, it seems difficult to achieve an equitable allocation of funds among the districts. Also, in the present procedure, it is difficult to consider the effects of various funding scenarios.

#### 4.2 Suggested Bridge Project Programming Procedure

The proposed IBMS would require the setting up of a bridge management group. This group would maintain the IBMS data base and the bridge history data base. The former would contain data needed to run the IBMS and the latter would contain records of all works done on individual bridges. The group would also be in charge of running the three sub-modules of the project selection module and preparing reports as needed. Figure 4.2 illustrates the position of the bridge management group in the proposed IBMS.

The bridge management group is recommended to reside in the Program Development Division of INDOT. The personnel in this group would be responsible for the orderly implementation of various elements of the IBMS. This group would consist of two sub-groups: the bridge inspection sub-group and the bridge activity programming sub-group. In this suggested organization, the bridge inspection group would have a direct involvement in the project selec-

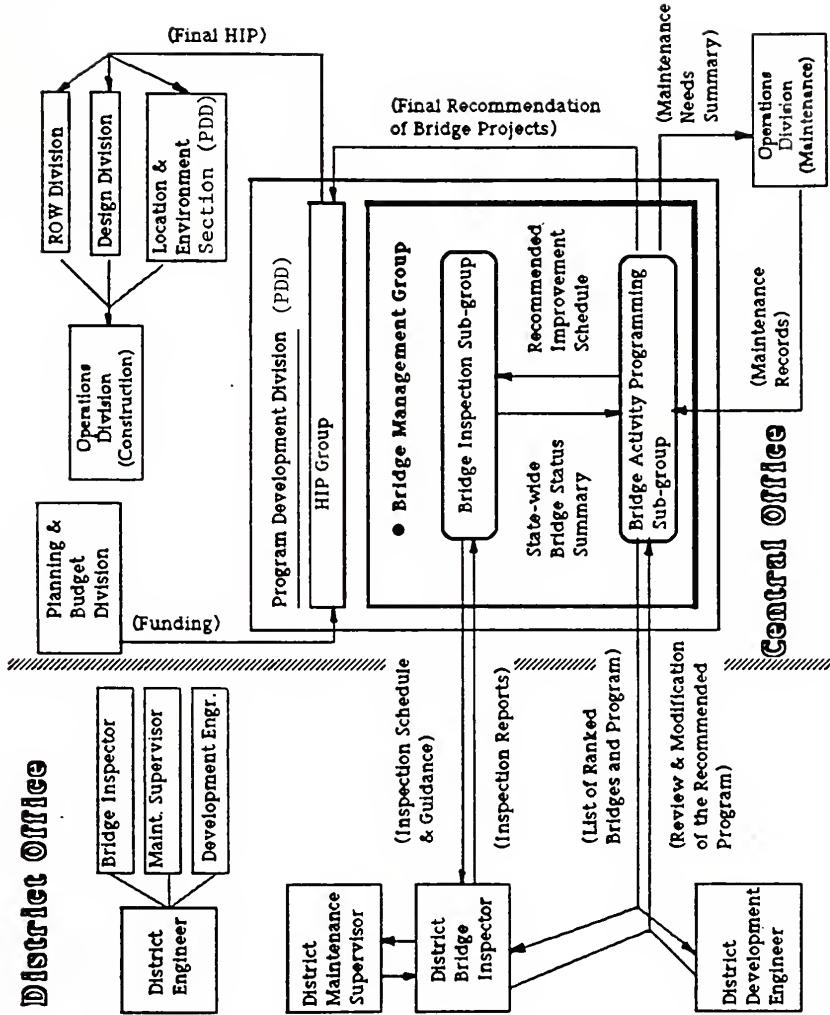


Figure 4.2 Suggested IBMS Organization

tion process and it would be responsible for maintaining and updating the IBMS data base. This sub-group would play an important role because the results of the project selection module are very dependent on the accuracy of the input data.

The bridge activity programming sub-group would run the three sub-modules of the project selection module. The district inspectors would be asked to recommend improvement alternatives. If life cycle cost analysis is needed for multiple alternatives for a bridge or if more than one bridge need to be compared, the life cycle cost analysis sub-module can be run to determine which improvement alternative or bridge should be evaluated. If only one option is recommended by the district inspector for the bridge, equivalent uniform annual cost would be computed and it would be used in the subsequent ranking sub-module. The ranking sub-modules would be run to prepare initial ranking lists. These lists would be sent to the district bridge inspectors for review and modification. Reviews and modifications would be discussed in a series of meetings between the bridge management group and the district director, development engineer and bridge inspectors.

After a consensus is achieved and agreements are made between the central office and the district offices upon the selection of bridges to be improved, the bridge activity programming sub-group would prepare a final improvement schedule and send it to the HIP group to have them considered along with other highway related projects. The necessary communication with other INDOT divisions would be done by the HIP group.

The bridge activity programming sub-group would communicate with the Maintenance Section of the Operations Support Division and would keep the

activity recording and monitoring data base up-to-date. This sub-group would prepare a maintenance need and backlog summary report which will be used by the Maintenance Section of the Operations Support Division and districts to manage the routine bridge maintenance program. In turn, the Maintenance Section would send copies of bridge maintenance accomplishment reports to the bridge activity programming sub-group for updating the activity history records. Activities accomplished must be reported bridge by bridge. Also, this sub-group would be in charge of analyzing historical data on cost and timing of improvement and maintenance activities and it would periodically update the IBMS.

It may be noted that the present channel of communication would generally be sufficient with only minor adjustments. However, a significant realignment would be necessary with respect to maintenance data. Figure 4.3 shows the flow of information related to maintenance in the proposed IBMS.

In summary, the organization of the proposed bridge management group would have two major changes over the existing procedure. First, the bridge inspection sub-group would become an integral part of the bridge programming process. The central office bridge inspectors have a global view of the bridges in the state system and at the same time they have direct interactions with the district inspectors who have up-to-date information on the current condition of bridges and their improvement needs. The direct involvement of the central office bridge inspectors into the programming procedure will help improve the communication between the district offices and the central office. Second, the bridge activity programming sub-group would serve as the in-house updating team that can continuously examine the effectiveness of the IBMS and make necessary modifications. It would keep direct contact with the

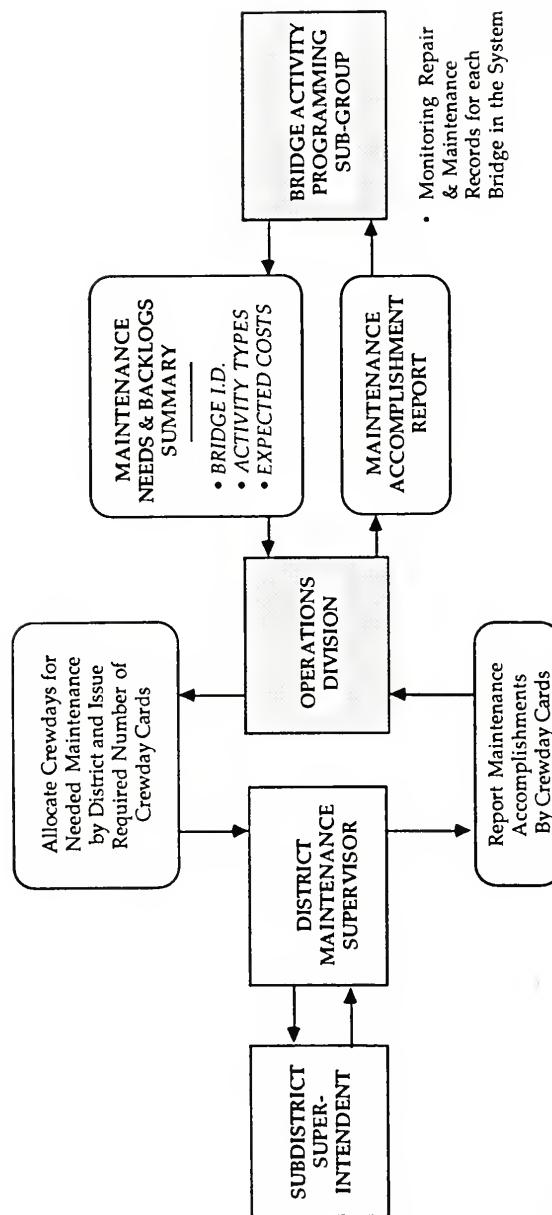


Figure 4.3 Flow of Bridge Maintenance Information.

Maintenance Section of the Operations Support Division and thus would bring maintenance planning close to improvement programming process. This sub-group would also be able to provide prompt information on the effect of various funding scenarios for use of the executive office or other divisions of the INDOT.



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